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EFFECT OF OPERATING VARIABLES ON POLLUTANT EMISSIONS FROM AIRCRAFT TURBINE ENGINE COMBUSTORS

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ABSTRACT

The purpose of this paper is to review NASA-Lewis combustor research aimed at reducing exhaust emissions from jet aircraft engines. Experimental results of tests performed on both conventional and experimental combustors over a range of inlet total pressure, inlet total temperature, reference velocity, and fuel-air ratio are presented to demonstrate the effect of operating variables on pollutant emissions. Combustor design techniques to reduce emissions are discussed. Improving fuel atomization by using an air-assist fuel nozzle has been shown to significantly reduce hydrocarbon and carbon monoxide emissions during idle. A short-length annular swirl-can combustor has demonstrated a significant reduction in nitric oxide emissions compared to a conventional combustor operating at similar conditions. The use of diffuser wall bleed to provide variable control of combustor airflow distribution may enable the achievement of reduced emissions without compromising combustor performance.

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EFFECT OF OPERATING VARIABLES ON POLLUTANT EMISSIONS FROM AIRCRAFT TURBINE ENGINE COMBUSTORS

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SUMMARY

The purpose of this paper is to review recent NASA-Lewis combustor research aimed at reducing or eliminating undesirable exhaust emissions from jet aircraft engines. Emission tests have been performed on both conventional and experimental combustors over a range of inlet total pressure, inlet total temperature, reference velocity, and fuel-air ratio. Experimental results are presented that demonstrate the effect of operating conditions on pollutant emissions from jet aircraft. Total hydrocarbons and carbon monoxide emissions are shown to increase markedly as fuel-air ratio is reduced below a value of about 0.01. This reduction is partly due to poor fuel atomization and partly due to the formation of fuel-air mixtures in the primary zone that are below the flammability limit. Total hydrocarbon and carbon monoxide emissions are shown to increase rapidly as a correlating parameter, P_3T_3/V_R, (in which P_3 is combustor inlet total pressure, T_3 is combustor inlet total temperature, and V_R is combustor reference velocity) is reduced below a value of about 10^5 lbs-sec-$^oR/ft^3$. The emission index for carbon monoxide is shown to be particularly sensitive to reference velocity. The emission index for the oxides of nitrogen is shown to increase with increasing inlet total temperature and decreasing reference velocity. For a given primary zone airflow distribution, smoke number is shown to increase with increases in combustor inlet total pressure and with decreases in com-

bustor inlet total temperature.

Experimental tests have shown that improving fuel atomization by using an air-assist fuel nozzle can significantly reduce hydrocarbon and carbon monoxide emissions during idle. Additional experimental designs are being investigated that optimize the local fuel-air ratio in the primary zone during idle by either (1) using diffuser wall bleed to control primary zone airflow or (2) by using staggered fuel nozzles. A short length annular swirl-can combustor has demonstrated a significant reduction in nitric oxide emissions compared to a conventional combustor operating at similar conditions. This reduction may be attributed to reduced reaction dwell time as a result of both reduced burning length and rapid mixing of combustion gases and dilution air. The premixing and carbureting of fuel and air in the swirl-can may also play a part in this nitric oxide reduction. An experimental combustor segment designed with increased primary zone airflow and increased mixing intensity has been tested that demonstrates extremely low smoke numbers at elevated pressures; however, the altitude relight capability of this configuration has not been satisfactory. Further research is being pursued to determine if techniques such as diffuser wall bleed may be used to control primary zone airflow so that lean primary zone fuel-air ratios can be obtained during take-off to reduce smoke formation and so that richer primary zone fuel-air ratios may be obtained during idle and altitude relight.

INTRODUCTION

Exhaust emission data from reference (1)* for a typical commercial jet engine are plotted against engine power setting in figure 1. The

*Numbers in parentheses designate references at end of paper.

products of inefficient combustion, carbon monoxide, and total hydrocarbons, are shown to be highest at a power setting of engine idle while oxides of nitrogen are shown to be highest during take-off. Lower combustion efficiency at idle is caused by (1) poor fuel atomization at low fuel flow rates, (2) lower fuel-air ratios, and (3) lower combustor inlet total pressure and temperature. Higher nitric oxide emissions during take-off are known to be caused by a higher combustor inlet total temperature which affects its rate of formation (ref. (2)). The data shown in figure 1 were obtained from a JT8D engine which has a compressor pressure ratio of 16:1. In general, it would be expected that engines with lower compressor pressure ratios would exhibit higher carbon monoxide and hydrocarbon emissions during idle while engines with higher compressor pressure ratios would exhibit higher nitric oxide emissions.

Smoke number usually tends to maximize at the take-off power setting. Reference (3) describes a recent effort by the airlines industry to retrofit an existing commercial engine with a combustor redesigned with increased primary zone airflow in order to reduce exhaust smoke density to a value below the threshold of visibility. The newer gas turbine engines are being designed with smoke numbers that are below the visible threshold of smoke.

Previous combustor design and development effort has been concentrated on the optimization of combustion efficiency, total-pressure loss, durability, exit temperature profile, and altitude relight. Recent research has been devoted to the development of short length combustors for advanced high-temperature gas turbine engines (ref. (4)). The additional requirement for both low gaseous emissions and low smoke number raises

the question as to the difficulty or even feasibility of attaining all of the prescribed emission limits without seriously compromising the other combustor performance criteria. In addition, the problem arises that a certain design change to minimize a given pollutant may inadvertently lead to an increase in some other pollutant. Combustor research is required to gain a better understanding of the design trade-offs that are necessary for minimizing pollutant emissions at various operating conditions and to devise new combustor design techniques to obtain reduced emissions without sacrificing engine performance. Furthermore, it is necessary to consider how future engine design requirements might be affected by a restraint on pollutant emissions.

The purpose of this paper is to review recent NASA Lewis combustor research (refs. (4) to (13)) aimed at reducing or eliminating undesirable exhaust emissions from jet aircraft engines. Emission tests were performed on both conventional and experimental combustors over a range of inlet total pressure, inlet total temperature, reference velocity, and fuel-air ratio. Total hydrocarbons, carbon monoxide, and nitric oxide concentrations and smoke number were determined from gas samples obtained at the exhaust plane of these test combustors. Experimental results are presented that demonstrate the effects of operating variables on both combustion efficiency and exhaust emissions. The relative influence of the various operating variables on the formation of each pollutant is discussed. Exhaust concentrations of total hydrocarbons, carbon monoxide, and nitric oxide expressed in terms of grams of pollutant per kilogram of fuel burned are plotted against the various combustor operating

variables and against a correlating parameter that has previously been used to analyze combustion efficiency data. Results are also presented from several experimental combustor configurations that have demonstrated reduced emission levels.

Most of the experimental data presented in this report that relates emissions with operating variables were obtained from a program (refs. (5) to (7)) in which a single J-57 combustor was tested in a 12-inch diameter housing. Tests were conducted at the following conditions: inlet total pressure, 1 - 20 atm; inlet total temperature, 100° - 600° F; reference velocity, 25 - 150 ft/sec; and fuel-air ratio, 0.004 - 0.015. Photographs of the test combustor used are shown in figure 2. Additional emission data are presented for an experimental annular swirl-can combustor that was designed for elevated combustor exit temperatures (refs. (8) and (9)). Design details of the swirl-can combustor are illustrated in figure 3. The swirl-can combustor was tested at the following operating conditions: inlet total pressure, 4 - 6 atm; inlet total temperature, 600° - 1050° F; reference velocity, 70 - 120 ft/sec; and exit total temperature, 1500° - 3500° F (fuel-air ratio, 0.015 - 0.062).

Smoke data, only, are presented from an experimental program (refs. (10) and (11)) in which a high pressure combustor was investigated. Design details of the experimental test segment are shown in figure 4. Smoke number data for this combustor are presented for the following range of test conditions: inlet total pressure, 10 - 27 atm; inlet total temperature, 400° - 900° F; reference velocity, 70 - 90; and fuel-air ratio, 0.007 - 0.013.

All test data presented in this report were obtained with ASTM A-1

fuel. The effect of other fuels or fuel additives on emissions will not be discussed in this report.

SAMPLING PROCEDURE

Specific details of the sampling procedures that were used in each research program are described in references (5) to (11). Practical considerations generally limited the number of gas sampling probes to one or two circumferential positions at the combustor exhaust plane at which a number of radial samples on the centers of equal areas were obtained, and then collected together as a single average sample. These probes were water-cooled to enable quenching of the reaction, and the samples were transferred through stainless steel sampling lines that were generally heated to above 300° F. Some of the gaseous emission samples were analyzed for total hydrocarbons by on-line equipment; however, most of the samples were collected in sampling vessels and analyzed at a later time. Total hydrocarbons were analyzed by means of a Beckman Model 106E flame ionization detector. Carbon monoxide was analyzed by a Beckman GC4 gas chromatograph, and oxides of nitrogen were determined by a modified Saltzman method based on reference (14). Smoke number was determined from the reflectivity of smoke traces collected on filter paper using the method of reference (15) with the exception that a continuous moving filter tape was used. A limited number of grab samples were analyzed for carbon dioxide and hydrogen. In the case of the research program described in reference (9), a fluidic oscillator was also used to determine the fuel-air ratio of the sample gas using the method of references (16) and (17).

The validity of the gas sample data was checked in specific instances

by comparing the combustion efficiency calculated from exhaust gas concentrations with combustion efficiency determined from thermocouple measurements, or by comparing the local fuel-air ratio deduced from exhaust gas concentrations with the fuel-air ratio determined by measured airflows and fuel flows. In general, the exhaust emission data checked rather well for test runs with combustion efficiencies greater than about 90 percent; however, as combustion efficiency measurements determined by thermocouples fell below 90 percent, the error in the exhaust sample increased greatly. Specifically, the total hydrocarbon concentration in the exhaust sample appeared to be much lower than that predicted from calculated combustion efficiencies from thermocouple measurements. The sampling error at low combustion efficiencies may be attributed to the following: (1) at low combustion efficiencies, especially at low combustor inlet total temperatures, liquid fuel may pass by the combustor exhaust plane and be undetected by the gas sample probes if the liquid is centrifuged onto the walls of the duct; (2) the use of only several circumferential sampling positions may in many cases not provide a representative exhaust sample, and (3) isokinetic sampling was not used. Despite the fact that the absolute accuracy of the exhaust emission data presented for low combustion efficiencies is in error, the emission trends with operating conditions should still be of relative significance.

All gaseous emission results presented herein are expressed in terms of an emission index in grams of pollutant per kilogram of fuel burned. The oxides of nitrogen present in the exhaust sample are believed to consist mainly of nitric oxide (NO) with lesser amounts of nitrogen dioxide

(NO_2); nevertheless, by convention, the emission index for the oxides of nitrogen is expressed in terms of grams of nitrogen dioxide (NO_2) per kilogram of fuel burned. In the text, this quantity will be referred to as either nitric oxide or oxides of nitrogen.

PRODUCTS OF INEFFICIENT COMBUSTION

EFFECT OF FUEL-AIR RATIO AND FUEL ATOMIZATION - Combustors for aircraft gas turbine engines are required to operate over a relatively wide range of fuel flows. Conventional combustors are, therefore, normally equipped with a dual range fuel nozzle consisting of a primary orifice to cover low fuel flows and a secondary orifice to handle high fuel flows that cuts in at higher pressure differentials across the fuel nozzle. Figure 5(a) shows a plot of combustion efficiency against fuel-air ratio for the J-57 test combustor. The combustion efficiency data presented in this report were determined from thermodynamic calculations using thermocouple measurements. The accuracy of the combustion efficiency data determined in this manner is estimated to be within about ±3 percent. These data were obtained at an inlet total pressure of 2 atm; an inlet total temperature of 300° F; and a reference velocity of 50 ft/sec. Data are presented for the production J-57 fuel system which contains six dual orifice nozzles and a modification thereof which incorporates air atomization. For the range of fuel-air ratio shown, only the primary orifice of the nozzle is used for the production model. The pressure drop across the production fuel nozzle is about 50 psi at a fuel-air ratio of 0.008 for this operating condition. Combustion efficiency is shown to fall off rapidly as fuel-air ratio is lowered below a value of about 0.01. This effect is attributed

to poor fuel atomization and reduced fuel penetration because, at low fuel flows, the pressure drop across the fuel nozzle is too low to provide effective swirl atomization. Poor fuel atomization causes larger fuel droplets to form which increases the time required for vaporization while reduced fuel penetration results in ineffective mixing of fuel and air.

The air-assist nozzle data shown in the same plot were obtained by connecting a source of high pressure air to the secondary orifice of the production model. A marked improvement in combustion efficiency is shown to be obtained by the introduction of the high pressure air which essentially improved fuel atomization of the production combustor. The improvement in combustion efficiency is especially large at the lowest fuel-air ratio where fuel atomization was the poorest for the production combustor. However, even with improved fuel atomization, there is still some reduction in combustion efficiency as fuel-air ratio is decreased. This may be attributed to the formation of fuel-air mixtures in the primary zone that are below the lean flammability limit. The data presented in figure 5 were obtained at a combustor inlet total pressure and temperature that are typical of the engine idle power setting. Additional data presented in reference (7) were obtained for higher combustor inlet total pressures and temperature for the same range of fuel-air ratio. A similar but less steep reduction in combustion efficiency with decreasing fuel-air ratio was observed. A higher combustion efficiency is, of course, expected at higher combustor inlet total pressures and temperatures, in addition, fuel atomization is greatly improved at higher fuel flows.

Figure 5(b) shows the corresponding hydrocarbon emission index plotted against fuel-air ratio for the same data. At a typical idle fuel-air ratio of 0.008 the hydrocarbon emission index was reduced from a value of 26.6 to a value of 3.3 by the improved fuel atomization of the air-assist nozzle configuration. Similarly figure 5(c) shows the emission index for carbon monoxide plotted against fuel-air ratio for the same data. At the typical idle fuel-air ratio of 0.008, the carbon monoxide emission index was reduced from a value of about 60 to a value of about 50. At fuel-air ratios below 0.008, the reduction in hydrocarbon and carbon monoxide emissions is quite pronounced when the air-assist nozzle configuration is used. The application of an air-assist fuel nozzle to reduce hydrocarbon and carbon monoxide emissions during idle is discussed in a later section of this paper.

EFFECT OF COMBUSTOR INLET TOTAL PRESSURE - The effect of combustor inlet total pressure on combustion efficiency of the J-57 combustor is shown in figure 6(a). These data were obtained at a reference velocity of 50 ft/sec; fuel-air ratios of 0.0075 and 0.013; and combustor inlet total temperatures of 300° and 600° F. Combustion efficiency is shown to decrease rapidly as combustor inlet total pressure is lowered below about 4 atm. The decrease in combustion efficiency is partly attributed to the reduction in inlet total pressure but is considered to be predominately caused by poor fuel atomization at the lowest combustor pressures as the result of low nozzle pressure drop. The tailed symbols shown on the plot indicate data points with nozzle pressure drops lower than 50 psi. Figures 6(b) and 6(c) show a corresponding increase in emission index for total hydrocarbons and for carbon monoxide as the

combustor inlet total pressure is reduced below a value of about 4 atm.

EFFECT OF COMBUSTOR INLET TOTAL TEMPERATURE - Figure 7(a) shows a plot of combustion efficiency against combustor inlet total temperature for values of fuel-air ratio of 0.013, inlet total pressures of 2 and 10 atm, and reference velocities of 50 and 100 ft/sec. Within the degree of accuracy of the data, combustion efficiency is not shown to be strongly affected by inlet total temperature for the range of data shown except at the higher reference velocity.

The hydrocarbon emission index results for the same data are shown plotted in figure 7(b). The rate of increase of hydrocarbon emissions with reduced combustor inlet total temperatures is shown to be greater for the data at the lower inlet total pressure. The corresponding increase in the carbon monoxide emission index with decreasing combustor inlet total temperature is shown in figure 7(c). The rate of increase in the carbon monoxide emission index with decreasing combustor inlet total temperature appears to be greatest for the data obtained at the lower inlet total pressure and higher reference velocity. It is interesting to note that the hydrocarbon and carbon monoxide emission indices show a significant increase with decreasing inlet total temperature even though combustion efficiency appeared rather insensitive to varying inlet total temperature. This is attributed to the fact that the over-all variation in emission level that was observed for some of the data corresponds to a change in combustion efficiency that is less than the experimental error in combustion efficiency determined from thermocouple measurements.

EFFECT OF COMBUSTOR REFERENCE VELOCITY - Reference velocity is defined as the total combustor airflow divided

by the product of combustor inlet density and maximum cross-sectional area. Figure 8(a) shows a plot of combustion efficiency against reference velocity for the J-57 combustor at an inlet total pressure of 2 atm; fuel-air ratios of 0.0075 and 0.013; and a range of inlet total temperature from 100° to 600° F. Limited data for the annular swirl-can combustor at an inlet total pressure of 4 atm; inlet total temperature of 600° F; and a fuel-air ratio of 0.023 - 0.024 are also presented. No significant effect of reference velocity on combustion efficiency is apparent for the data obtained from either combustor at an inlet total temperature of 300° and 600° F. However, at an inlet total temperature of 100° F, there appears to be a relatively strong effect of reference velocity on combustion efficiency for the J-57 combustor. Similar low inlet total temperature data for the annular swirl-can combustor were not available. Combustion efficiency decreases from a value of about 90 to about 80 percent as reference velocity is increased from about 75 to 150 ft/sec at an inlet total temperature of 100° F and a fuel-air ratio of 0.013. The data obtained at inlet total temperature of 100° F at both a fuel-air ratio of 0.0075 and 0.013 indicate that combustion efficiency tends to fall off slightly as reference velocity is reduced from a value of about 75 ft/sec, to a value of about 50 ft/sec. Previous results have shown, that for most combustors, combustion efficiency decreases with increasing reference velocity; however, for some combustors, a maximum value of combustion efficiency occurs at a specific value of reference velocity, and will then decrease as reference velocity is either increased or decreased. A reduction in combustion efficiency with increasing reference velocity may be attributed to a reduction in flame

stability and dwell time; while a reduction in combustion efficiency with decreasing reference velocity may be attributed to either poor mixing as the result of a lowering in combustor pressure drop or to poor fuel atomization as the result of a lowering in fuel nozzle pressure drop as fuel flow is lowered.

The data for the hydrocarbon emission index shown in figure 8(b) tend to follow the trend that would be expected from figure 8(a). The highest hydrocarbon emission indices occur for the data at a combustor inlet total temperature of 100° F. The hydrocarbon emission index for these data tend to reach a minimum at a reference velocity of 75 ft/sec. Similarly, figure 8(a) indicated a peak combustion efficiency for these data at 75 ft/sec. The carbon monoxide emission index for these data are shown plotted in figure 8(c). These results show a continuous increase in carbon monoxide emissions as reference velocity is decreased. This may be attributed to the strong effect that combustor dwell time has on the oxidation of carbon monoxide formed in the primary zone. Apparently as dwell time is reduced, lesser amounts of carbon monoxide are oxidized to carbon dioxide. These data for the J-57 combustor indicate that the increase in carbon monoxide emissions with increasing reference velocity is strong even at an inlet total temperature as high as 300° F. At similar operating conditions, the effect of reference velocity on the hydrocarbon emission index appears to be the same for both combustors shown; however, the rate of increase in the carbon monoxide emission index appears to be greater for the swirl-can combustor than for the J-57 combustor when compared at the same inlet total temperature of 600° F.

EFFECT OF CORRELATING PARAMETER - Previous studies have correlated combustion efficiency against a combustion parameter composed of inlet total pressure, P_3, multiplied by inlet total temperature, T_3, and divided by reference velocity, V_R (ref. (18)). In general, this technique of correlating combustion efficiency data provides a single correlating curve for only a single value of fuel-air ratio for a given combustor or combustor type. Combustion efficiency is plotted against the correlating parameter P_3T_3/V_R in figure 9(a). These data were obtained for the J-57 combustor at a fuel-air ratio of 0.013. All of the data shown tend to correlate with the P_3T_3/V_R parameter except for the data with a fuel nozzle pressure drop below 50 psi. The data obtained at a low nozzle pressure drop would not be expected to follow the correlation because of the overriding effect of poor fuel atomization. Corresponding hydrocarbon and carbon monoxide emission indices are plotted for these same data against the correlating parameter in figure 9(b) and (c). Total hydrocarbon and carbon monoxide emissions are shown to increase rapidly as the correlating parameter, P_3T_3/V_R is reduced below a value of about 10^5 lb-sec-$^oR/ft^3$.

OXIDES OF NITROGEN

EFFECT OF COMBUSTOR INLET TOTAL TEMPERATURE - The effect of combustor inlet total temperature on the emission index for oxides of nitrogen for both the J-57 combustor and swirl-can combustor is shown plotted in figure 10. The J-57 data were obtained at a reference velocity of 50 ft/sec, fuel-air ratio of 0.013, and inlet total pressure of 2 atm, while the swirl-can data were obtained at a reference velocity of 99-109 ft/sec, fuel-air ratio of 0.016, and inlet total pressure of

4 to 6 atm. The emission index for oxides of nitrogen is shown to increase quite rapidly as inlet total temperature is increased beyond a value of about 600° F. Similar results were reported in reference (19). The increase in the emission index for oxides of nitrogen with increasing inlet temperature is attributed to an increase in formation rate because of increasing flame temperature.

Facility capabilities limited the maximum inlet total temperature to 600° F for the J-57 combustor tests. Other J-57 combustor data presented in reference (7) over a range of inlet total temperature of 100°-600° F for other operating conditions display a great deal of scatter; nevertheless the general trend of these results is similar to that shown in figure 10. Part of this data scatter may be indicative of the difficulty in obtaining accurate oxide of nitrogen samples at exhaust concentrations below 50 ppm. Since the Saltzman analysis technique used was estimated to be accurate to within about ±1 ppm, the bulk of the error may be attributed to either (1) nonrepresentative sampling or (2) adsorption of a portion of the oxides of nitrogen in the sampling system.

EFFECT OF COMBUSTOR REFERENCE VELOCITY - The effect of combustor reference velocity on emission index of the oxides of nitrogen for both the J-57 combustor and swirl-can combustor is shown in figure 11. The J-57 data were obtained at an inlet total temperature of 600° F, fuel-air ratio of 0.013, and an inlet total pressure of 2 atm, while the swirl-can data were obtained at an inlet total temperature of 600° F, fuel-air ratio of 0.023-0.024, and an inlet total pressure of 4 atm. The results from both combustors indicate a rather significant increase in nitric oxide emissions with decreasing reference

velocity at an inlet total temperature of 600° F. Since the formation rate of nitric oxide is reaction rate controlled, the quantity formed would be expected to be proportional to the dwell time in the reaction zone. It is reasonable to expect that dwell time would be inversely proportional with combustor reference velocity. Similar data obtained at other values of inlet total temperature for both combustors indicate that the rate of increase in the emission index for oxides of nitrogen with decreasing reference velocity becomes greater as the inlet total temperature is increased.

EFFECT OF FUEL-AIR RATIO - The effect of fuel-air ratio on emission index for oxides of nitrogen for both the annular swirl-can combustor and J-57 combustor is shown plotted in figure 12. As described in references (8) and (9), the annular swirl-can combustor has been designed for high exit temperature operation and has been tested up to a combustor exit temperature of about 3600° F. These data for the swirl-can combustor were obtained at an inlet total temperature of 600° F, inlet total pressure of 4-5 atm, and reference velocity of 67-74 and 81-88 ft/sec. The J-57 data were obtained at an inlet total temperature of 600° F, inlet total pressure of 10-12 atm, and reference velocity of 50 ft/sec. The emission index for oxides of nitrogen for the swirl-can combustor increases with increasing fuel-air ratio and then reaches a peak value at a fuel-air ratio of about 0.03 before leveling off again. The nitric oxide emissions for the J-57 combustor appear to increase with increasing fuel-air ratio; however, the scatter in these data and other similar data presented in reference (7) makes it difficult to precisely define the effect of fuel-air ratio for

the range of data studied.

EFFECT OF COMBUSTOR INLET TOTAL PRESSURE - Exhaust emission tests have been conducted on the J-57 combustor over a range of inlet total pressures of 1-20 atm (ref. (7)). At the lower end of this range in inlet total pressure (under 4 atm), where inlet total pressure has an influence on combustion efficiency, the emission index for oxides of nitrogen tends to increase with increasing inlet total pressure. This effect may be attributed to an increase in the bulk temperature of the primary zone because of increased combustion efficiency. However, variations in any other operating variables that increase combustion efficiency have also been observed to increase nitric oxide emissions. Above 4 atm, nitric oxide emissions appeared to be insensitive to variations in inlet total pressure; however, there is considerable scatter in these data thus leaving some question as to the validity of this conclusion.

EFFECT OF CORRELATING PARAMETER - The emission index for oxides of nitrogen is shown plotted against the correlating parameter, P_3T_3/V_R, in figure 13. These data from the J-57 test combustor were obtained at a fuel-air ratio of 0.013. Despite a great deal of data scatter, there is a general tendency for nitric oxide emissions to increase with increasing values of P_3T_3/V_R. This effect is mainly attributed to increasing flame temperature and increasing dwell time which are effected by increasing inlet total temperature and decreasing reference velocity, respectively, as has been shown in the previous sections of this report. Inlet total pressure has been observed to have no effect on the nitric oxide emission level except at low

values of inlet total pressure where increasing total pressure has a strong effect on improving combustion efficiency. In all cases studied, increasing combustion efficiency has been shown to increase the quantity of nitric oxide that is formed.

No attempt has been made to improve the correlation shown by this figure. The correlating parameter, P_3T_3/V_R probably has limited applicability considering the fact that the data presented in figure 13 were limited to a maximum value of inlet total temperature of 600° F and previous results shown herein for the swirl-can combustor and the results of reference (19) indicate a rapid increase in nitric oxide emissions as T_3 is increased above a value of 600° F. However, refinements in sampling procedure to obtain more accurate nitric oxide emission data are required prior to seeking improvements in data correlation.

SMOKE NUMBER

The present criterion used to determine acceptable smoke number values for jet aircraft is that the smoke plume be invisible. Tentative correlations between smoke number and smoke plume visibility (ref. (20)) have indicated that for typical jet aircraft engines a smoke number value of 25 or less is acceptable for eliminating smoke visibility. References (21) to (28) have discussed techniques for minimizing smoke number by means such as increasing primary zone airflow and improving fuel-air mixing in the primary zone. The oxidation of carbon formed in the primary zone has also been recognized as an important step in controlling exhaust smoke level. Figure 14 compares the smoke intensity (expressed as a carbon emission index) in the primary zone to that at the combustor exhaust for the high pressure combustor (fig. 4) described in refer-

ence (10). Primary zone smoke concentrations were determined from infra-red spectral radiance measurements. These results were obtained for a combustor configuration designed with a lean, intensely mixed primary zone that had smoke number of 32 at a fuel-air ratio of 0.013. Even in a combustor designed for low smoke formation, a significant quantity of soot is formed in the primary zone that is later oxidized before leaving the combustor. Similar results were reported in reference (26). Despite the apparent importance of the soot oxidation step, results to date from short-length experimental combustor tests have not indicated any effect of combustor length on smoke number.

EFFECT OF COMBUSTOR INLET TOTAL PRESSURE - The effect of combustor inlet total pressure on smoke number for several experimental combustors is shown in figure 15. The data presented for the J-57, swirl-can, and high pressures combustors (Models A and C of ref. (10)) were obtained at a combustor inlet total temperature of 600° F. Data for several production engines including the J8D (with and without retrofitted combustor to reduce smoke), JT9D, and CF6 are shown for comparison. Smoke number tends to increase with combustor inlet total pressure to varying degrees for different combustor configurations depending upon airflow distribution and mixing intensity. The experimental combustor configurations with the lower smoke numbers are known to have serious altitude relight limitations. Techniques for obtaining satisfactory altitude relight capabilities with combustors that have low smoke numbers will be discussed in a later section.

EFFECT OF COMBUSTOR INLET TOTAL TEMPERATURE - The effect of combustor inlet total temperature on smoke number for a standard and mod-

ified J-57 combustor (ref. (5)) and an experimental high pressure combustor (ref. (10)) is shown in figure 16. The J-57 combustor data were obtained at an inlet total pressure of 12.3 atm, a fuel-air ratio of 0.013, and a reference velocity of 54 ft/sec while the experimental high pressure combustor data were obtained at an inlet total pressure of 10 atm, a fuel-air ratio of 0.013, and a reference velocity of 60 - 90 ft/sec. The reduction in smoke number with increasing inlet total temperature has also been observed in reference (29). This effect may be beneficial in mitigating the effect of increased inlet total pressure in engines with higher compressor pressure ratios.

EFFECT OF OTHER VARIABLES - In general, over-all fuel-air ratio has not been observed to have a strong influence on smoke number. Increasing fuel-air ratio increases smoke number for some configurations and decreases it for others. In tests performed on the high temperature swirl-can combustor over a range of fuel-air ratio of 0.017 to 0.059 at an inlet total temperature of 600° F, inlet total pressure of 3 - 4 atm, and reference velocity of 70 - 100 ft/sec, smoke number was near zero for values of fuel-air ratio below 0.042 and approached a value of 24 at a fuel-air ratio of 0.059. The effect of fuel-air ratio on smoke number for the J-57 combustor was observed to be negligible at inlet total pressure of 12.3 atm, inlet total temperature of 600° F, and reference velocity of 54 ft/sec for a range of fuel-air ratio of about 0.007 to 0.013. Results similar to those shown in figure 14 for the high pressure experimental combustor have shown a small increase in smoke number with decreasing fuel-air ratio. This effect may be attributed to the formation of local fuel-rich zones because

of poor atomization at low fuel flows.

Data presented in reference (29) for the Phillips 2-inch combustor indicated a negligible effect of combustor reference velocity on smoke number. Experimental data for the J-57, swirl-can and high pressure combustor to demonstrate the effect of reference velocity on smoke number has not been obtained systematically. An increase in reference velocity could conceivably decrease smoke number for a specific combustor geometry if the resulting increase in pressure loss tended to improve the primary zone mixing intensity.

No precise relationship exists between combustion efficiency and smoke number. The existence of smoke in the combustor exhaust represents only a fraction of a percent loss in combustion efficiency. A higher smoke number due to a fuel-rich primary zone design is often characteristic of a combustor configuration with both good combustion stability and good combustion efficiency. For a given combustor geometry, modifications made to reduce smoke number will generally reduce altitude relight capability.

TECHNIQUES TO REDUCE EXHAUST EMISSIONS

TOTAL HYDROCARBONS AND CARBON MONOXIDE - Results presented in reference (6) for the J-57 combustor that were described in a previous section (fig. 5) have shown that improving fuel atomization by using an air-assist fuel nozzle can significantly reduce unburned hydrocarbon and carbon monoxide emissions at idle operating conditions. The effect of atomizer air pressure drop on combustion efficiency and emissions at the same conditions as the data in figure 5 at a fuel-air ratio of 0.008 is shown in figure 17. A significant reduction

in total hydrocarbon and carbon monoxide was obtained using an atomizer air pressure drop as low as 100 psi. The quantity of compressed air required to achieve the reductions in emissions shown in figure 17 amounts to less than 0.5 percent of the total combustor airflow at idle. This might be obtained from engine compressor bleed by using an auxiliary supercharger with a compression ratio of about 4.3. The secondary orifice of the fuel nozzle could be used for this purpose during idle operation, but for all other conditions, the secondary orifice could be used to handle the higher fuel flow as done conventionally in a dual orifice fuel nozzle.

Another method being studied to reduce emissions at idle is fuel staging with the objective of operating at locally higher fuel-air ratios in the primary zone during idle to achieve higher combustion efficiency without increasing overall engine fuel flow. This might be accomplished by providing separate fuel manifolds and controls either (1) to adjacent fuel nozzles in a conventional annular combustor or (2) to separate radial zones of fuel injection as in the swirl-can combustor (fig. 3) or the double-annular ram induction combustor (ref. (4)).

An additional approach for improving combustion efficiency at idle would be to shift the combustor airflow distribution so that less air is introduced into the primary zone, thereby increasing the local fuel-air ratio in the primary zone in addition to lowering local velocities. To perform this function by means of a mechanical flow splitter or variable-area air entry port could be quite difficult and complicated because of the high temperature environment. NASA/Lewis is examining an approach for varying primary zone airflow by equipping the diffuser with wall

bleed. Tests on a small-scale wide-angle annular diffuser using wall bleed (ref. (12)) have demonstrated that the radial velocity profile may be shifted to either the hub or tip by independently controlling the quantity of bleed on the inner and outer wall of the diffuser. This technique could be used as shown in figure 18. During idle when combustor pressure drop is low, wall bleed would not be used; however, the combustor inlet would purposely be designed unsymmetrical to the combustor liner in order to allow most of the air to bypass the primary zone. During takeoff and cruise when the combustor pressure drop is higher, wall bleed would be used to adjust the inlet radial velocity profile to introduce more air into the primary zone. Engine cycle efficiency would not be sacrificed because this bleed air could be used for turbine cooling. The same technique could be applied to improve altitude windmill relight capabilities.

OXIDES OF NITROGEN - Over the past several years, NASA/Lewis has been conducting research aimed at reducing combustor length in high temperature turbine engines in order both to minimize combustor wall coolant requirements and to minimize overall engine weight (ref. (4)). Fortuitously, the short-length combustor technology developed for these purposes provided us with a combustor with a short dwell time that has been shown to be effective in reducing the formation of oxides of nitrogen. Tests performed on the swirl-can combustor (fig. 3) described herein have demonstrated a significant reduction in nitric oxide emissions compared to a conventional combustor operating at similar conditions. The use of fuel prevaporization or fuel-air premixing may also be useful in reducing nitric oxide emissions. Never-

theless, the reduction of oxides of nitrogen in high compressor pressure ratio engines or regenerative engines which operate at combustor inlet total temperatures of 1000° F or greater may necessitate the use of water injection. Water injection reduces the quantity of oxides of nitrogen formed by decreasing flame temperature.

SMOKE NUMBER - As indicated in the previous section, techniques for eliminating visible smoke plumes by increasing primary zone airflow and mixing intensity are already being utilized in advanced gas turbine engine designs. However, altitude relight capabilities may be seriously jeopardized in future higher compressor pressure ratio engines when increased primary zone airflow is used to reduce smoke number below a value of 25 (threshold of visible smoke). The technique of diffuser bleed described previously could help alleviate this design problem.

CONCLUDING REMARKS

The results presented herein have demonstrated that the degree of difficulty in obtaining low emissions is partly dependent on engine compressor pressure ratio. Hydrocarbon and carbon monoxide emissions at idle are more difficult to control for low compressor pressure ratio engines, while nitric oxide emissions and smoke at takeoff are more difficult to control for high compressor pressure ratio engines. The trend in large jet engines to higher compressor pressure ratios suggests that in the future the control of both oxides of nitrogen and smoke may become a more challenging problem. It is difficult at this time to speculate on the possible influence of emission regulations on future aircraft engine designs. Much will depend on how methods required to reduce

emissions affect other performance criteria. Several techniques that could be used to control emissions are discussed herein. These approaches are not necessarily final solutions, but are indicative of possible directions to take in reducing emissions without penalizing combustor performance.

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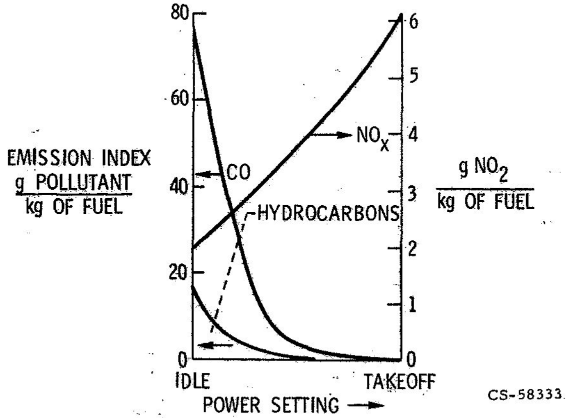
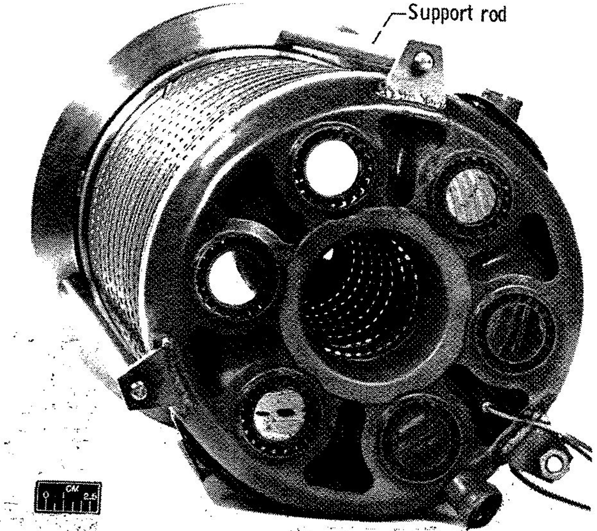
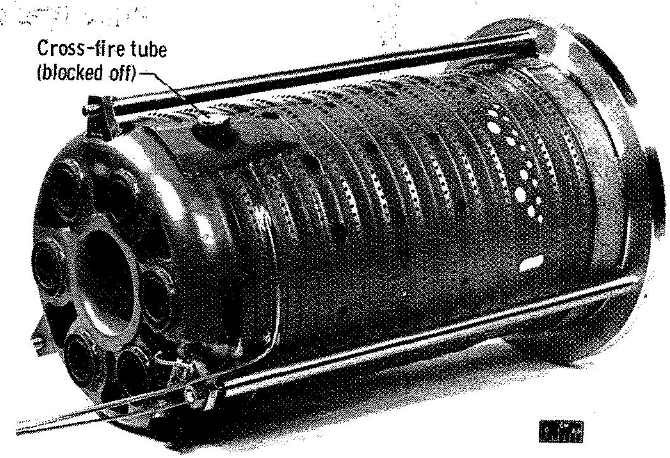


Figure 1. - Effect of engine operating conditions on exhaust emissions of JT8D engine.



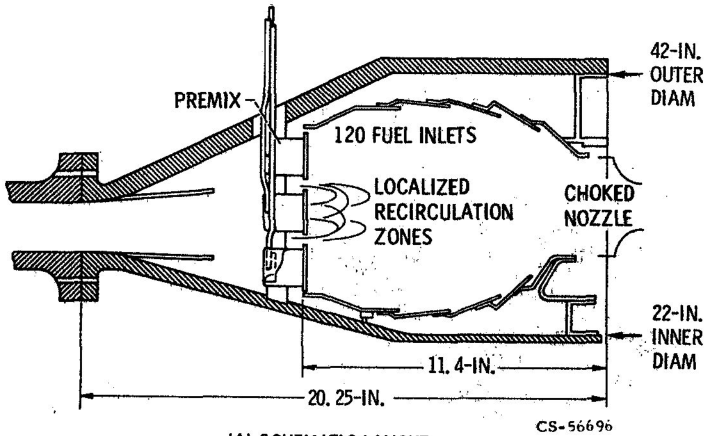
(a) Upstream view.



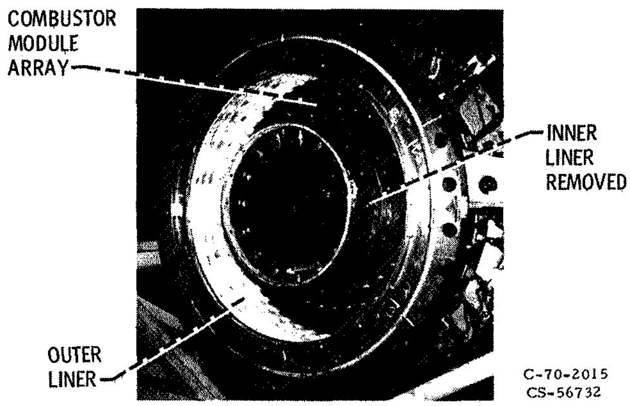
(b) Side view.

Figure 2. - J-57 combustor liner.

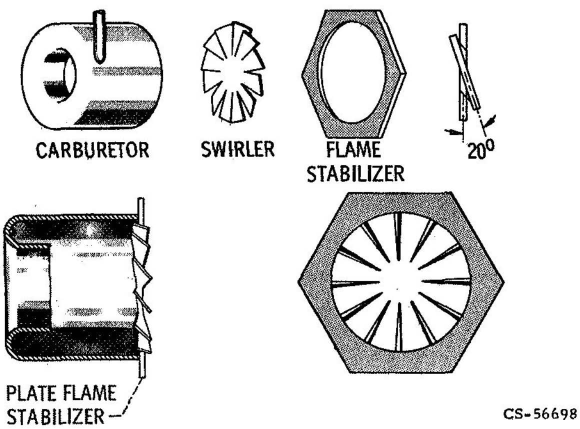
E-6460



(A) SCHEMATIC LAYOUT.

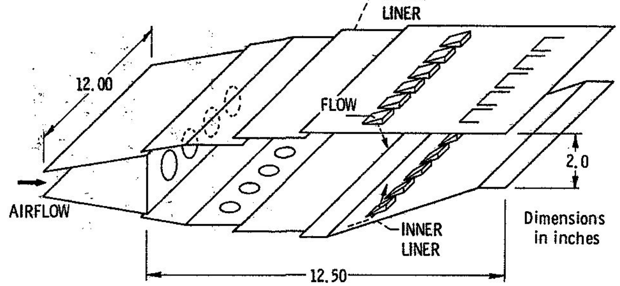


(B) PHOTOGRAPH (LOOKING UPSTREAM).

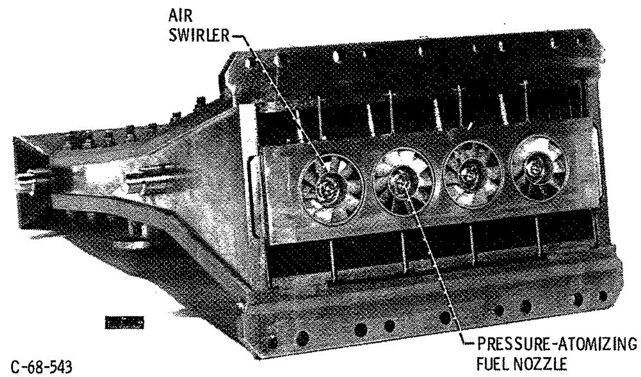


(C) COMBUSTOR MODULE DETAILS.

Figure 3. - High temperature swirl-can combustor.



(a) SCHEMATIC SKETCH OF COMBUSTOR.



(b) DIFFUSER AND COMBUSTOR INLET.

Figure 4. - Experimental high pressure combustor test segment.

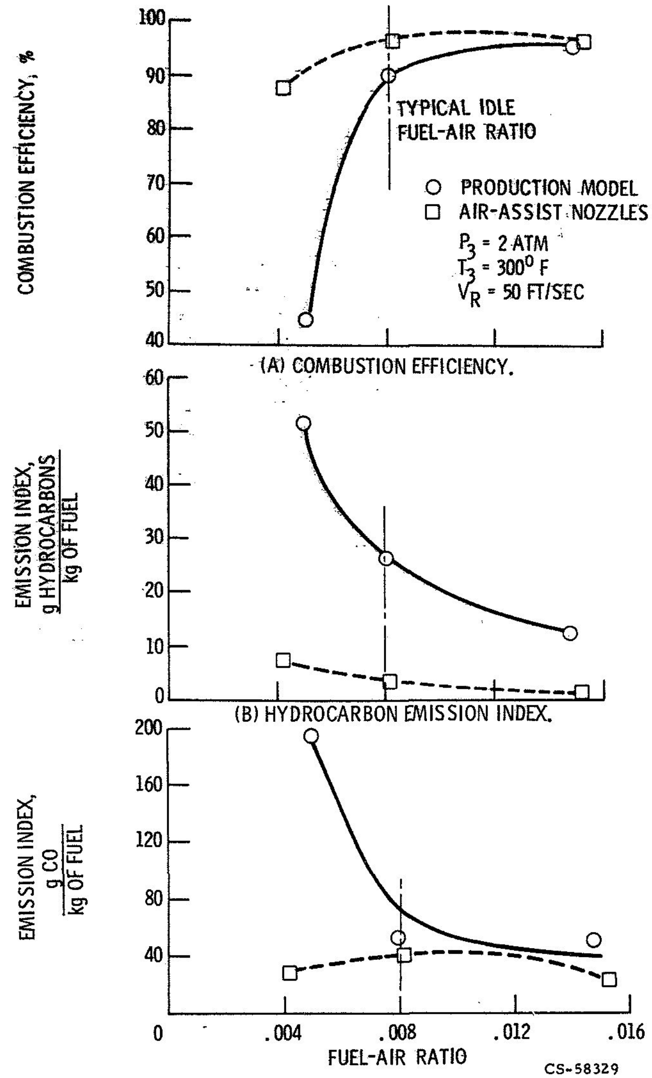
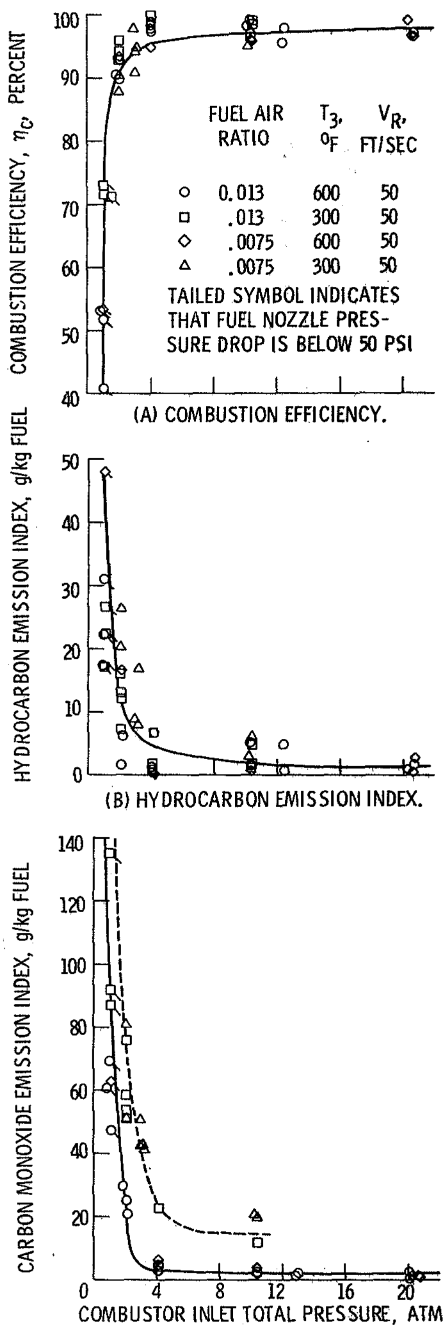


Figure 5. - Effect of fuel-air ratio and fuel atomization on products of inefficient combustion for the J-57 combustor.

E-6480



(C) CARBON MONOXIDE EMISSION INDEX.

Figure 6. - Effect of combustor inlet total pressure on products of inefficient combustion for the J-57 combustor.

E-6400

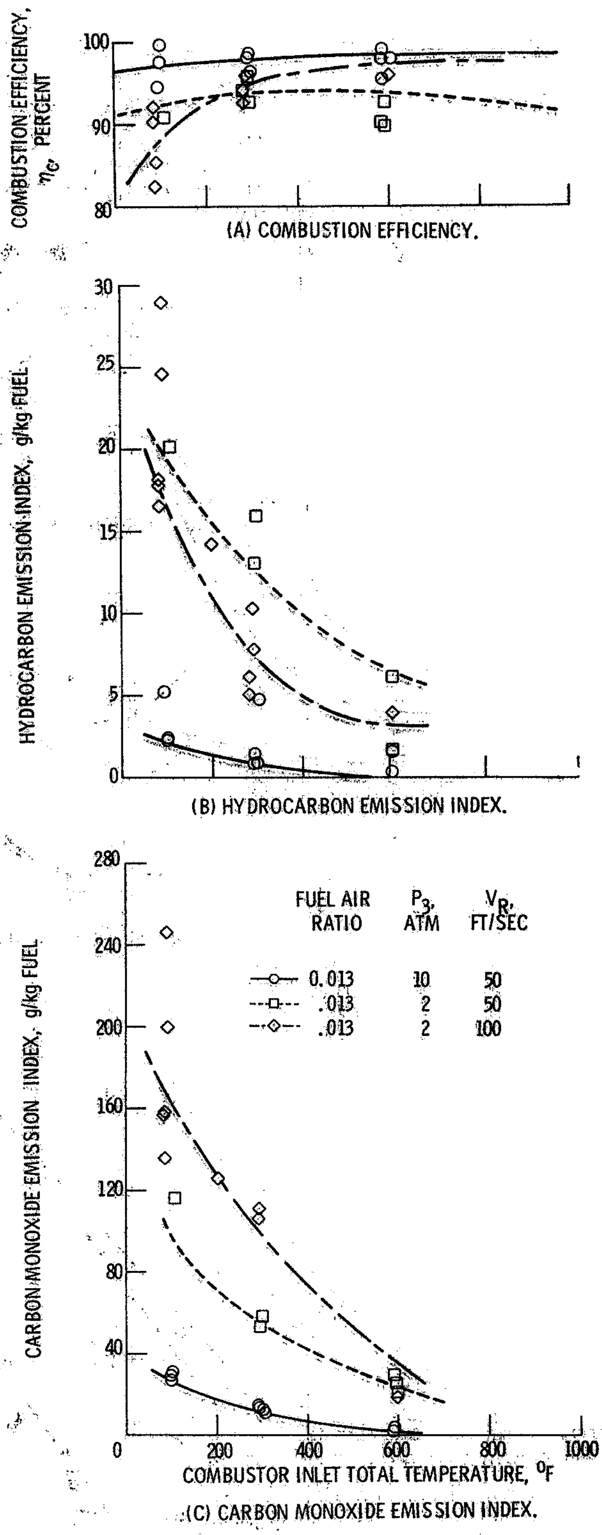


Figure 7. - Effect of combustor inlet total temperature on products of inefficient combustion for the J-57 combustor.

E-6480

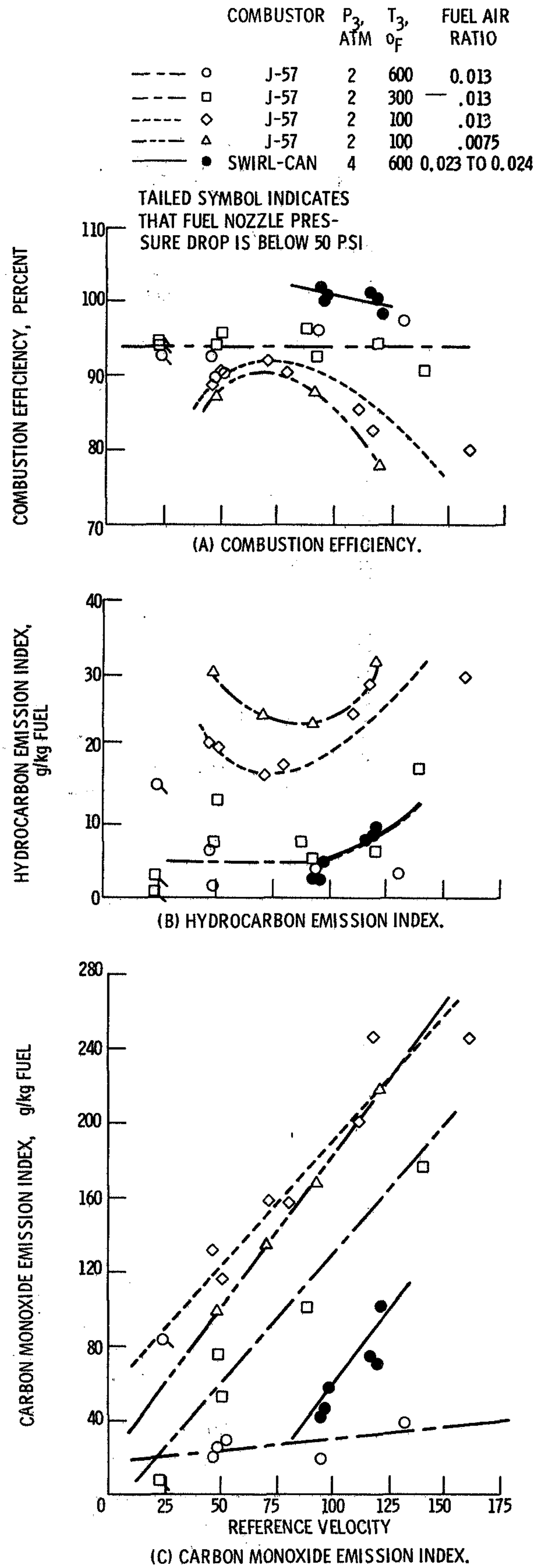
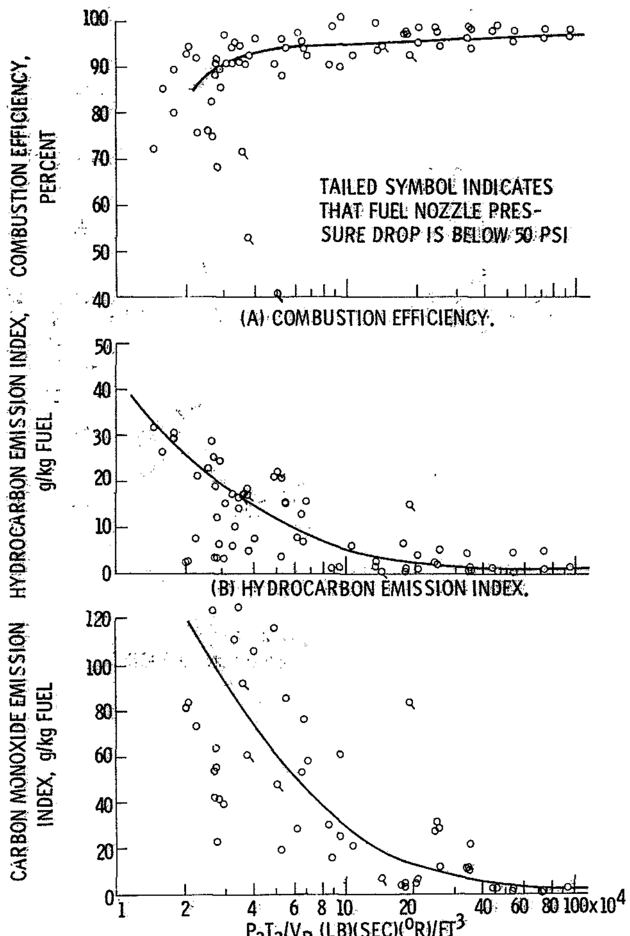


Figure 8. - Effect of combustor reference velocity on products of inefficient combustion for the J-57 and swirl can combustors.



(C) CARBON MONOXIDE EMISSION INDEX.

Figure 9. - Effect of correlating parameter on products of inefficient combustion for the J-57 combustor. Fuel-air ratio, 0.013.

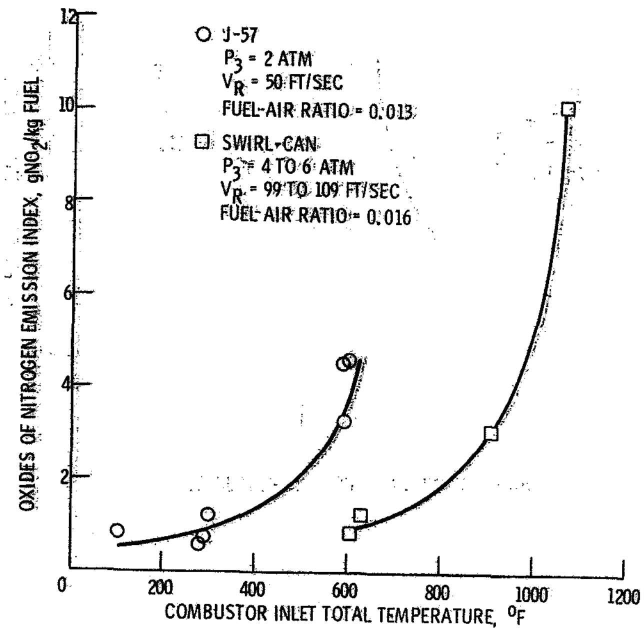


Figure 10. - Effect of combustor inlet total temperature on emission index for oxides of nitrogen.

E-6460

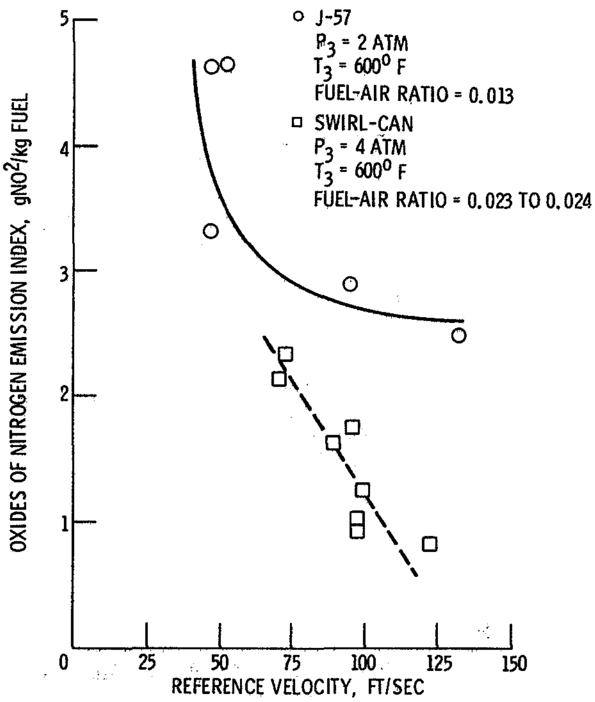


Figure 11. - Effect of combustor reference velocity on emission index for oxides of nitrogen.

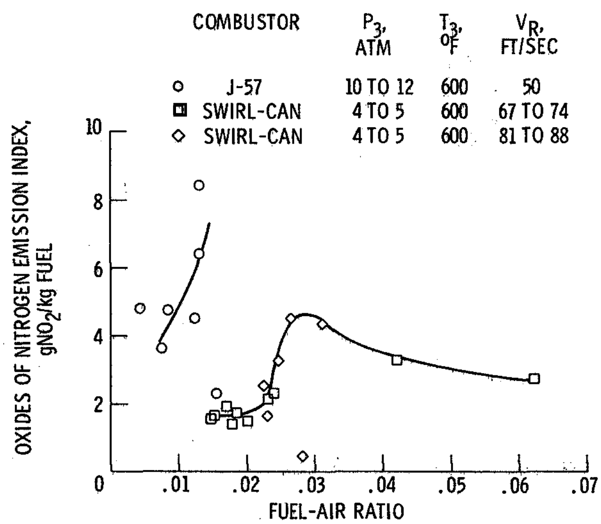


Figure 12. - Effect of fuel-air ratio on emission index for oxides of nitrogen.

E-6480

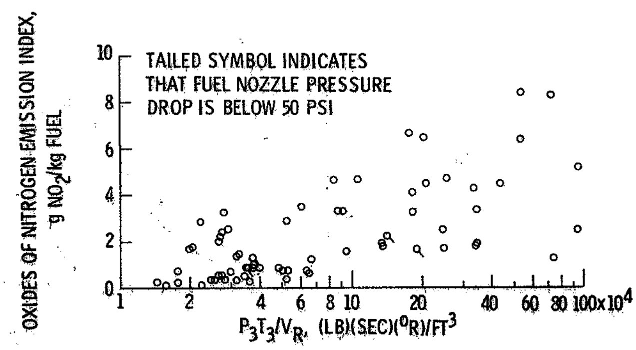


Figure 13. - Variation of emission index for oxides of nitrogen with correlating parameter for the J-57 combustor. Fuel-air ratio, 0.013.

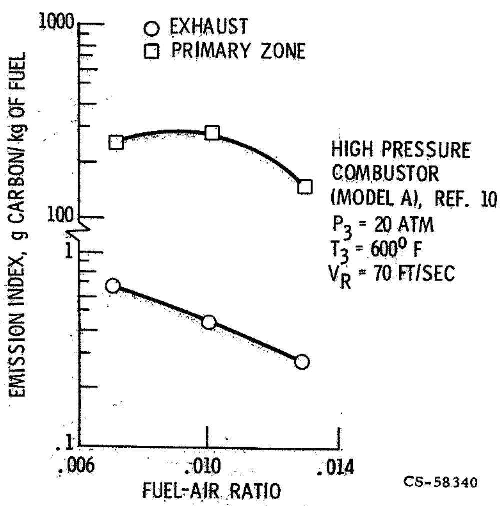


Figure 14. - Effect of fuel-air ratio on smoke formation.

E-6480

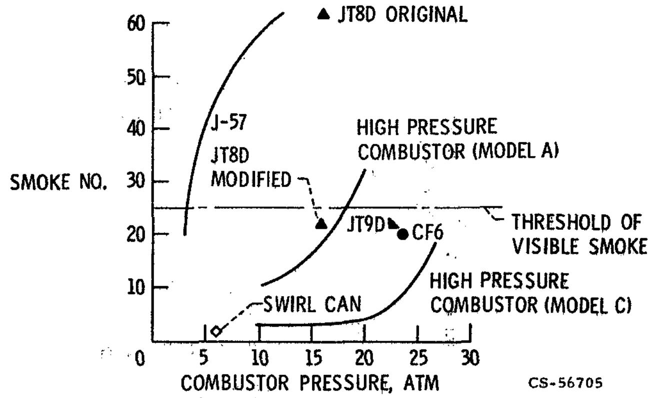


Figure 15. - Effect of combustor pressure on smoke.

COMBUSTOR	P_3, ATM	FUEL-AIR RATIO	V_R, FT/SEC
○ J-57 (STANDARD)	12.3	0.013	54
□ J-57 (MODIFIED)	12.3	.013	54
◇ HIGH PRESSURE (MODEL C)	10	.013	60 TO 90

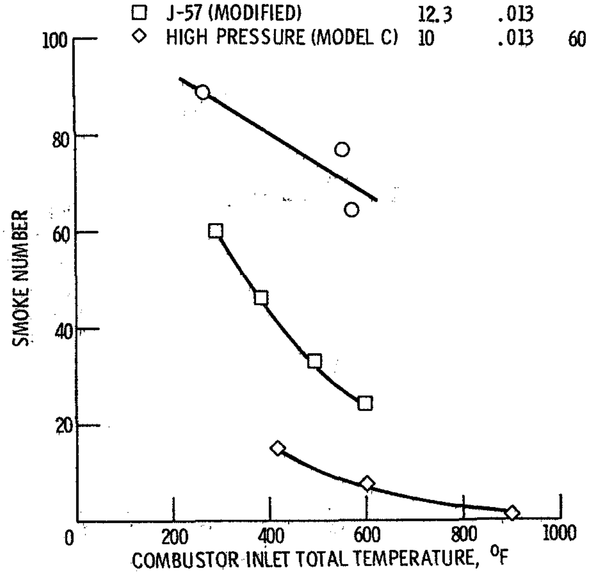


Figure 16. - Effect of combustor inlet total temperature on smoke number.

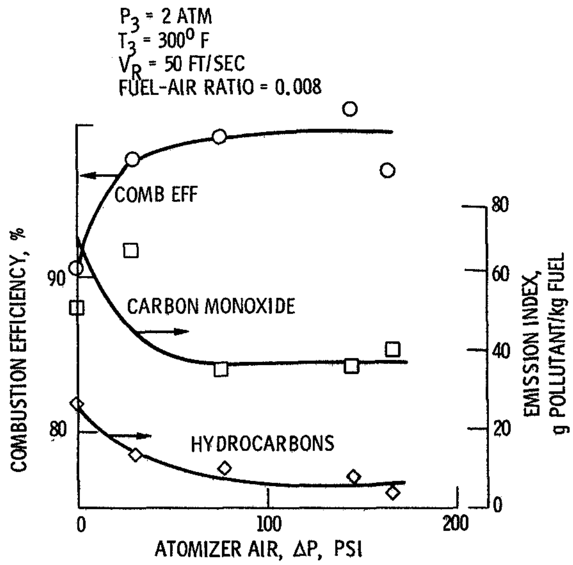


Figure 17. - Reduction in emissions at idle using air-assist fuel nozzle.

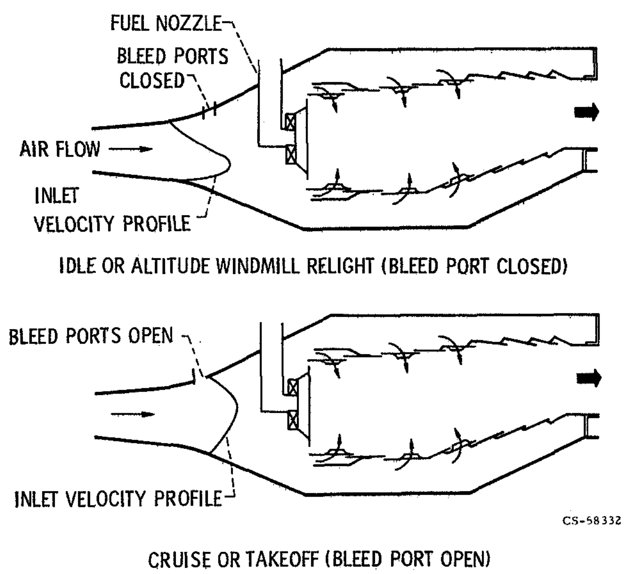


Figure 18. - Use of diffuser wall bleed to control combustor airflow distribution.